INDAL TECHNOLOGIES

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IMPROVING THE DESIGN & ECONOMICS OF DARRIEUS ROTOR WIND TURBINES

Report on Tasks 5 & 6
(Cost Estimates, Final Report)

Prepared for

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ABSTRACT

This report presents the final results of a study of the feasibility of improving the cost effectiveness of Darrieus rotor wind turbines. The key feature of the improvement is the incorporation of "tailored" airfoils which have been designed (and proven) to limit the maximum power developed by the rotor. In this way a larger area may be swept and more energy extracted from the wind without increasing the (considerable) costs of the drive train, electrical generators and connections, foundations, and necessary services.

Two new rotors have been designed (in a preliminary manner) and arrangement drawings have been prepared. One rotor is limited to using a blade obtainable as a single aluminum extrusion while the second rotor incorporates a step-tapered blade and larger chord dimensions. The cost and energy production of each (based on a 20-machine installation) is compared with equivalent costs for the existing Indal 6400 wind turbine.

Results show that the greatest cost of energy decreases are associated with the second rotor (with tapered blades) and with lower wind regimes. For the PEI North Cape location a cost of energy decrease of 21% is anticipated.

It is recommended that further (detailed) design concentrate on rotor #2 (with tapered blades) and that special attention be given to the design of blades, their connections, and aerodynamic fairings.

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1.0 INTRODUCTION

1.1 Background

Despite the recent drop in world prices for oil and other conventional energy sources, it is regarded as inevitable that the costs of energy will again increase. This price rise, coupled with concerns with the environmental effects of many of today's practices, is likely to lead to greater demand for "clean" alternative sources. The source which is considered to have the greatest untapped potential is energy from the wind.

Most wind turbines fall into one of two categories: horizontal or vertical axis machines. The former consists of machines having one or more propeller blades and an axis of rotation aligned with the wind direction. The class of vertical axis wind turbines (VAWT) includes the Darrieus rotor having curved airfoil section blades connected to the central rotating axis at the upper and lower roots; the profile follows a curve that minimizes the bending due to centrifugal action. This concept was patented by its inventor in 1931 (1)* but was not seriously developed until its "rediscovery" by the staff of the National Research Council (NRC) of Canada in the 1960's.

The commercial development of the Darrieus rotor has therefore lagged behind that of horizontal axis wind turbines (HAWTs) but evidence suggests that the cost of

*Numbers in parenthesis refer to references listed in Section 6.

power produced by VAWTs will be competitive with or cheaper than that from HAWTs. This is due to the simplicity of design in which the machine is insensitive to wind direction, the blades are restrained by at least two connections, and all the drive train and generators are mounted close to the ground.

Development of the Darrieus rotor in North America has been centered at the NRC, Ottawa, and at Sandia National Laboratories (SNL), Albuquerque, New Mexico. At both locations much work has been carried out into the aerodynamic performance, the effect of blade profiles, solidities, the number of blades, etc. Most of the development of computer models to simulate the structural response has been done by SNL and Indal Technologies (2).

In Albuquerque testing has been done on several wind turbines, the largest being a 25.5 x 17.0 m VAWT.

At Southern California Edison's test site in California, an Indal Technologies Inc. Series 6400, rated at 500 kW, has been tested since 1983. In Canada several 16m x 11.2m machines, rated at 50 kW, have been in operation for a number of years and in 1984 the Atlantic Wind Test Site (AWTS) on Prince Edward Island began operating an Indal Technologies Inc. 6400 - 500 kW VAWT.

Considerable experimental data have therefore been collected documenting the performance and structural response of the Darrieus rotor. Furthermore, the economic viability of these machines has been demonstrated in California.

The progress achieved in the development and commercialization of the Darrieus rotor has, therefore, been impressive. However, there remain some important steps yet to be taken in improving the economics of these machines. One such step is the incorporation of airfoils which have been designed especially as part of the wind turbine system.

1.2 Tailored Airfoils

The economics of wind turbine manufacture and operation is affected by many factors. Among the more important factors is the cost of the transmission and the electrical generators which is commonly at least 60% of the total cost (3). These components must be sized to match the maximum power that will be captured by the rotor although this maximum power may be reached on relatively few occasions if sufficiently high windspeeds are infrequent (as is often the case). It is, therefore, of economic advantage to limit the peak power generated by the rotor.

In recognition of this situation there has been considerable research recently in the United States into developing a family of airfoils especially suited to vertical axis wind turbines (4,5). These airfoils exhibit stall at lower angles of attack than do the NACA00 series used until now, and thereby limit the aerodynamic lift and rotor power.

The performance of these special airfoils have been studied in wind tunnel tests (6) and have been confirmed by Sandia National Laboratories where they were installed

as the central sections of their 17m test rotor (7). Not only was the peak power output lowered but the value of the lead-lag cyclic stresses was also reduced. In addition, the wind tunnel tests have indicated that surface roughness (from insect accumulation, for example) will affect the performance of tailored airfoils no more than it affects the conventional NACA00 airfoils (5).

The properties of these "tailored" airfoils have also been utilized by Sandia National Laboratories in the design of their planned 34m large test bed machine (6,7). This machine, which is claimed to offer cost-of-energy reductions of 20%, will be erected in 1986 and may pave the way for a new generation of more competitive vertical axis wind turbines.

1.3 Methodology

The overall objective of this project has been to investigate the technical and economic feasibility of incorporating tailored airfoils into a Darrieus rotor wind turbine. This report presents the results of Phase 1 of a larger project which may possibly comprise up to four parts:

Phase 1 - Technical Feasibility & Economic Assessment
Phase 2 - Detailed Design of Selected Rotor
Phase 3 - Rotor (and Module) Fabrication
Phase 4 - Installation and Testing

The terms of reference and basic assumptions for the present Phase 1 study are listed below.

(1) Two new rotors are examined: one has a constant blade chord of .763 m with a tailored airfoil while the other combines the tailored airfoil with a step-tapered chord resulting in a greater chord dimension near the upper and lower blade roots.

(2) The rated power of the two new rotors will be approximately 520 kW (electrical) at sea level. This is the same as the present Indal Technologies Inc. 6400 VAWT.

(3) The remaining design details will be based upon those of the existing Indal Technologies Inc. 6400 VAWT.

(4) Both rotors will be designed to maximize energy output in a Rayleigh wind distribution having a mean value (at 10m height) of 16 mph (7.15 m/s).

This project has been divided into the following six tasks:

Task 1	Rotor Configuration
Task 2	Structural Analysis
Task 3	Preliminary Design
Task 4	Arrangement Drawings
Task 5	Cost Estimating
Task 6	Final Report

The results of Tasks #1, 2, 3 and 4 have already been presented to the client. However, their findings are summarized in Section 2.0 of this report. Section 4 presents the cost estimating results of Task #5 and the overall conclusions of cost effectiveness and the subsequent recommendations are included in Section 5.

1.4 Statement of Work

The Statement of Work for Task #5 (Cost Estimating) and Task #6 (Final Report) are reproduced from the contract document.

Task #5. Cost Estimating

Objectives

1) To obtain approximate costs for all major components of both rotors so that the cost increase or decrease relative to the Indal Technologies Inc. 6400 may be obtained.

2) To estimate the cost of transportation to and installation at the selected Canadian sites (Magdalen Islands and PEI).

Approach

1) It is impossible to obtain firm costs of a project when detail drawings, production numbers and financing details are not available. Therefore, meaningful relative costs will be used.

2) The following cost basis will be used.

- costs will be in current (1985) Canadian dollars;
- all relevant customs, federal and provincial taxes will be included;
- production and installation of twenty machines is assumed;

- costs associated with the Indal Technologies Inc. 6400 Series VAWT will be adjusted where appropriate;
- full overhead rates and profit margins will be included.

Output

The results of the cost estimating will be used in the Final Report of Task #6.

Task #6. Final Report

Objectives

1) To summarize the results of the previous Tasks.

2) To present a cost analysis (compared with the existing Indal Technologies Inc. 6400) of setting up a twenty-machine windfarm in the selected locations.

3) To predict the percentage cost of energy reductions that may be achieved in comparison with existing VAWTs.

Approach

1) This Task will result in a report which will summarize all of the work which has led up to the final cost of energy predictions.

2) The selected sites for the twenty-machine windfarm are: Prince Edward Island (North Cape) and Magdalen Islands (near the site of the earlier DAF 250 kW

VAWT). The wind regimes that have been measured at these sites will be used to calculate the total energy production. In addition, reasonable assumptions will be made for the cost of operating and maintaining the windfarm.

Output

The Final Report will include the following:

1) A summary of the findings of Tasks #1 through 5.

2) The increase in energy capture and the increase in manufacturing costs associated with the two new rotors proposed.

3) Estimates of the decrease in the cost of energy associated with windfarms in the two selected locations.

4) A summary of all assumptions made in carrying out calculations or in estimating costs.

5) Conclusions concerning the effectiveness of using tailored and tapered airfoils in reducing the cost of energy.

2.0 REVIEW OF PREVIOUS TASKS

Four tasks have previously been completed. Their results were presented in two reports due to logical association between Tasks #1 and 2 and between Tasks #3 and 4; they will be summarized in the same two groupings.

2.1 Task #1 (Rotor Configuration) and Task #2 (Structural Analysis)

2.1.1 Objectives

1) Update existing computer programs for calculating performance and energy output to incorporate multiple airfoil dimensions and types.

2) Identify a rotor having a constant 0.763 m (30 inch) chord with a maximum electrical output of 520 kW and having acceptable structural response.

3) Identify a rotor having non-constant chord blades and minimal struts with a maximum electrical output of 520 kW and acceptable structural response.

2.1.2 Procedure

As for any design procedure, the identification of acceptable configuration involved a number of iterations of proposing certain geometries, calculating their performance and energy output, and then checking the structural response. The results of this Task reflects the final iteration.

The following structural analyses were carried out on all final configurations.

1) Identification of the first twelve natural frequencies at the operating speed. Preparation of a fan plot of natural frequencies vs. rotor speed.

2) Examination of the forced response of the rotor to the aerodynamic loads caused by a steady ambient windspeed of 20 m/s (45 mph). Calculation of the rms of the cyclic stresses.

3) Non-linear static response of the stationary rotor to a "survival" wind of 67 m/s (150 mph).

4) Application of a transient torque equivalent to a static load of 4.0 times the mean torque at rated power.

The blades and their connections have proven to be the critical design items of Darrieus rotors. It was assumed that the blade material would be 6061-T6 aluminum alloy and that, as implied in Figure 2.1, a maximum value for the rms of cyclic stresses (at a windspeed of 45 mph) is 12.0 MPa (1,740 psi).

2.1.3 Results

The outlines of the two configurations finally selected are shown in Figures 2.2 and 2.3. The corresponding energy outputs are summarized in Table 2.1 where they are compared with the corresponding performance of the existing Indal 6400 wind turbine. This table shows

that in high windspeed locations (mean annual speed = 8.05 m/s) energy increases of 20% and 36% can be expected, while in lower wind regimes (V = 6.26 m/s) the energy output may be up to 52% greater than that of the Indal 6400.

Fan plots for the two rotors are presented in Figures 2.4 and 2.5 which also show the frequencies of the cyclic excitation forces. In general, the dangerous resonance conditions involve odd excitation harmonics (1P, 3P, etc.) with butterfly modes, or propeller modes with even harmonics.

Rotor #1 would appear to be clear of direct resonances while rotor #2 has a possible conflict near 5P. However, this crossing is not likely to be serious and later adjustments should ensure limited response.

The mean and dynamic stresses at key locations of the two blades at a windspeed of 45 mph are summarized in Tables 2.2 and 2.3. These tables show that both designs meet the suggested ceiling of 11.7 MPa (1,700 psi) for the rms of cyclic stress in a 20 m/s (45 mph) windspeed and will, therefore, have an adequate fatigue life.

The responses of the two rotors to a survival wind loading are summarized in Tables 2.4 and 2.5; neither set of blades appears to suffer undue stresses.

2.2 Task #3 (Preliminary Design) and Task #4 (Arrangement Drawings)

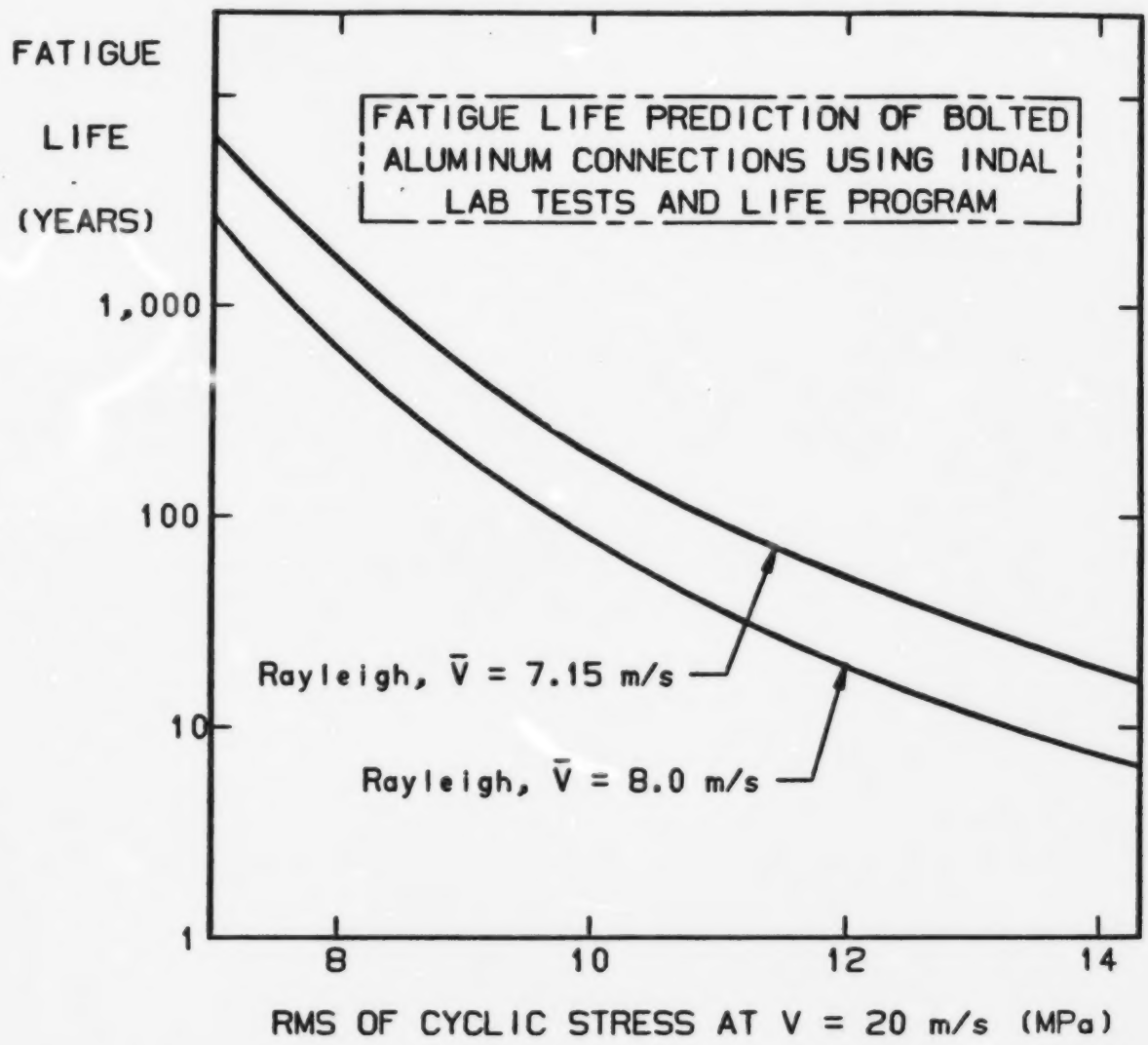


Figure 2.1. Relationship Between rms of Cyclic Stress and Fatigue Life

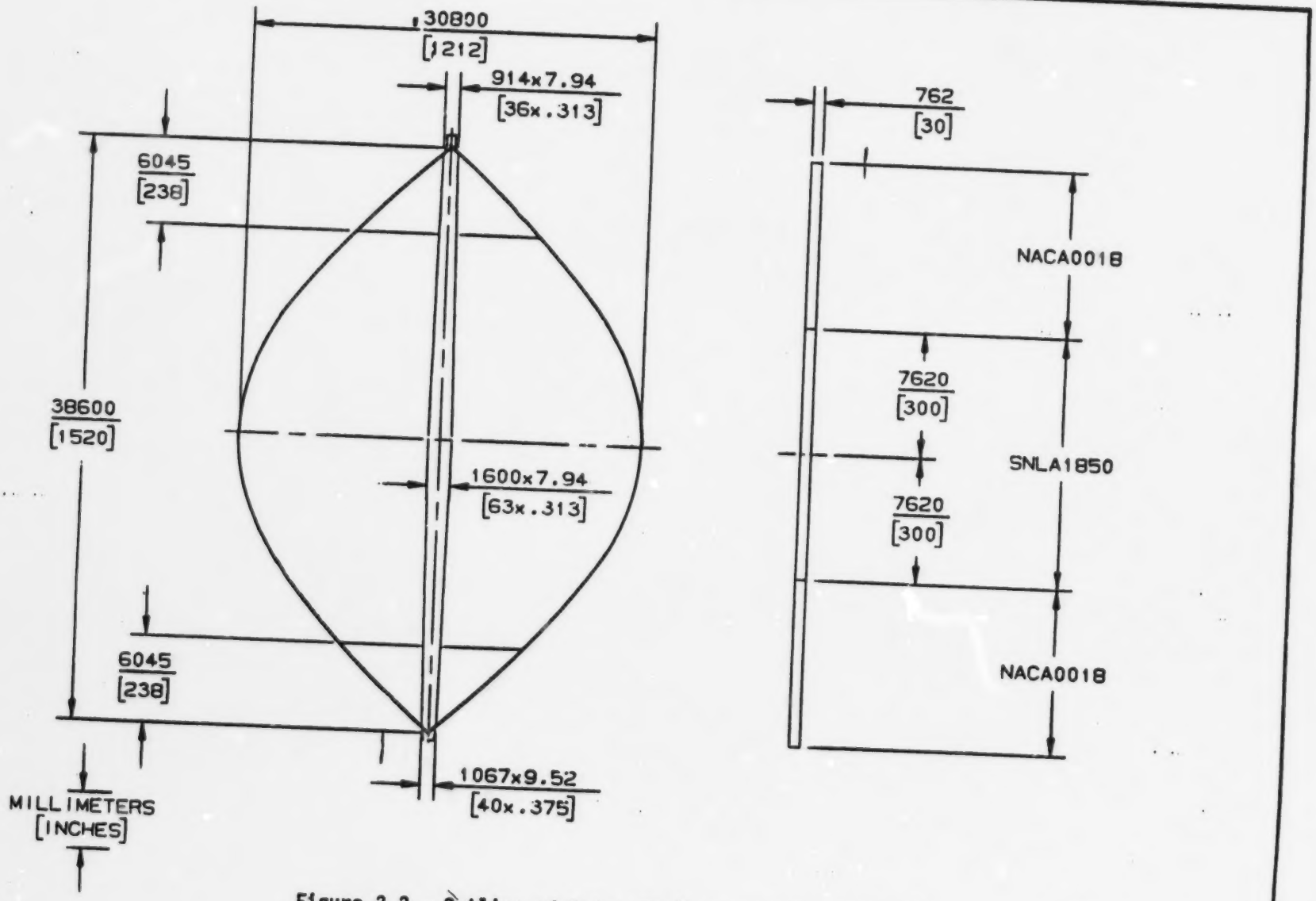


Figure 2.2. Outline of Rotor #1 (Constant Chord Blade)

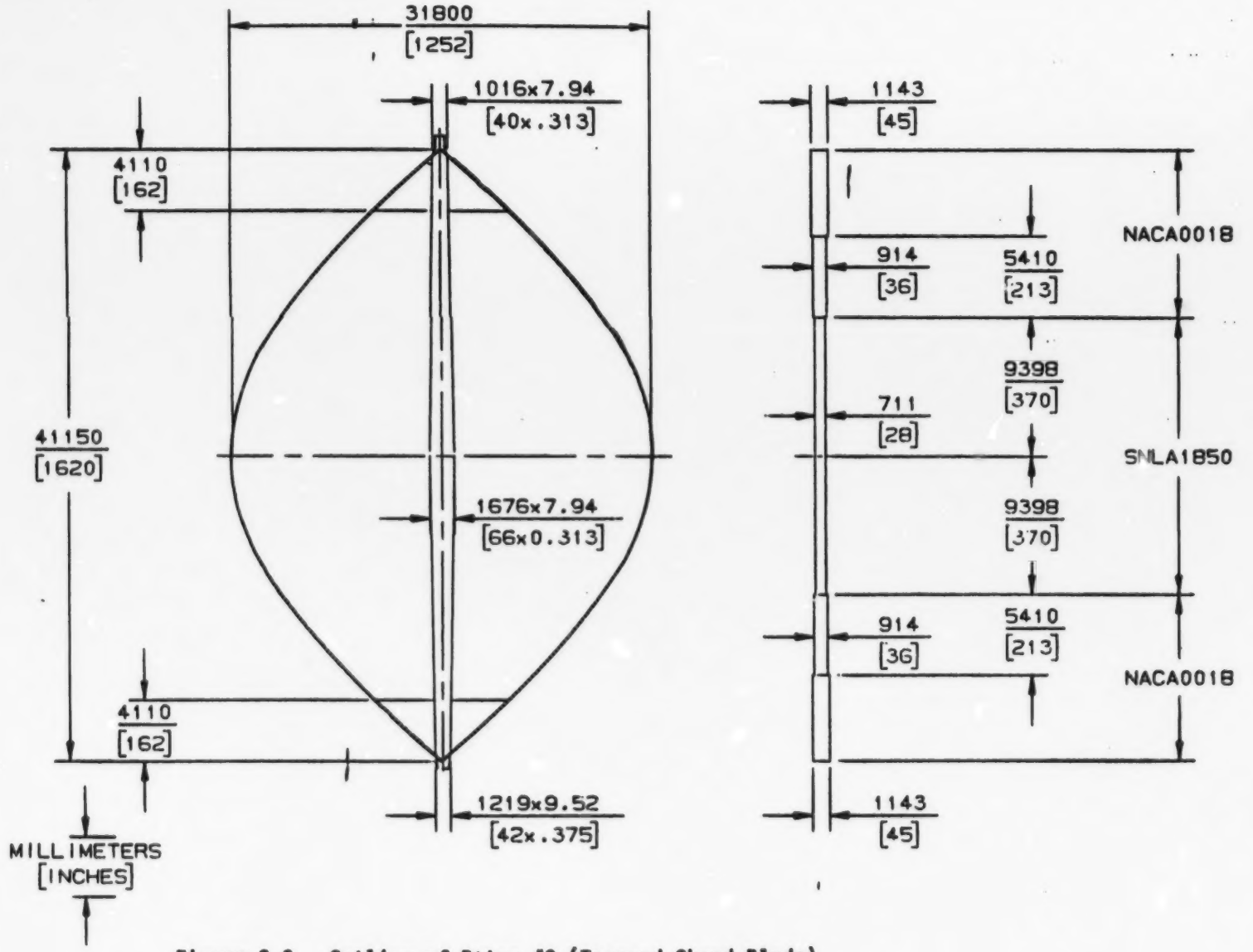


Figure 2.3. Outline of Rotor #2 (Tapered Chord Blade)

TABLE 2.1. SUMMARY OF PERFORMANCE OF NEW ROTORS AND THE INDAL 6400

	Indal 6400	Rotor #1 Constant Chord	Rotor #2 Tapered Chord
rotor height, m	36.6	38.6	41.1
rotor diameter, m	25.1	30.8	31.8
H/D ratio	1.46	1.25	1.29
swept area, m^2	605	786	891
rotor speed, rpm	45.0	41.0	38.0
max. elect. output, kW	520	520	520
at V=8.05 m/s (Rayleigh)			
annual energy, MWh	1154	1381	1566
% increase	0%	20%	36%
annual energy, MWh/m^2	1.91	1.76	1.76
at V=7.15 m/s (Rayleigh)			
annual energy, MWh	874	1075	1248
% increase	0%	23%	43%
annual energy, MWh/m^2	1.44	1.37	1.40
at V=6.26 m/s (Rayleigh)			
annual energy, MWh	606	770	920
% increase	0%	27%	52%
annual energy, MWh/m^2	1.00	0.98	1.03

Note: Windspeeds are given at a 10 m reference height and assume a wind shear exponent of 0.16.

2.2.1 Objectives

1) Use the rotor geometries and load levels identified in Tasks #1 and 2 to carry out preliminary design of the critical components of both rotors.

2) Prepare a set of arrangement drawings which, in conjunction with existing drawings, will allow cost estimates to be obtained.

2.2.2 Procedure

For each of the wind turbines, the following components/assemblies were considered.

- guy cable system
- blades
  - root connections
  - splice connections
  - strut-blade connections
- horizontal struts
- central column
- upper bearing
- lower coupling
- power module

A number of new engineering drawings were prepared and, where possible, existing drawings were modified. The new drawings were required principally for the new airfoil extrusions, the splice connections (especially those combining blades of different chord), and the horizontal strut details.

The struts are similar to those which have recently been fitted to the Indal 6400 at AWTS, PEI, but the

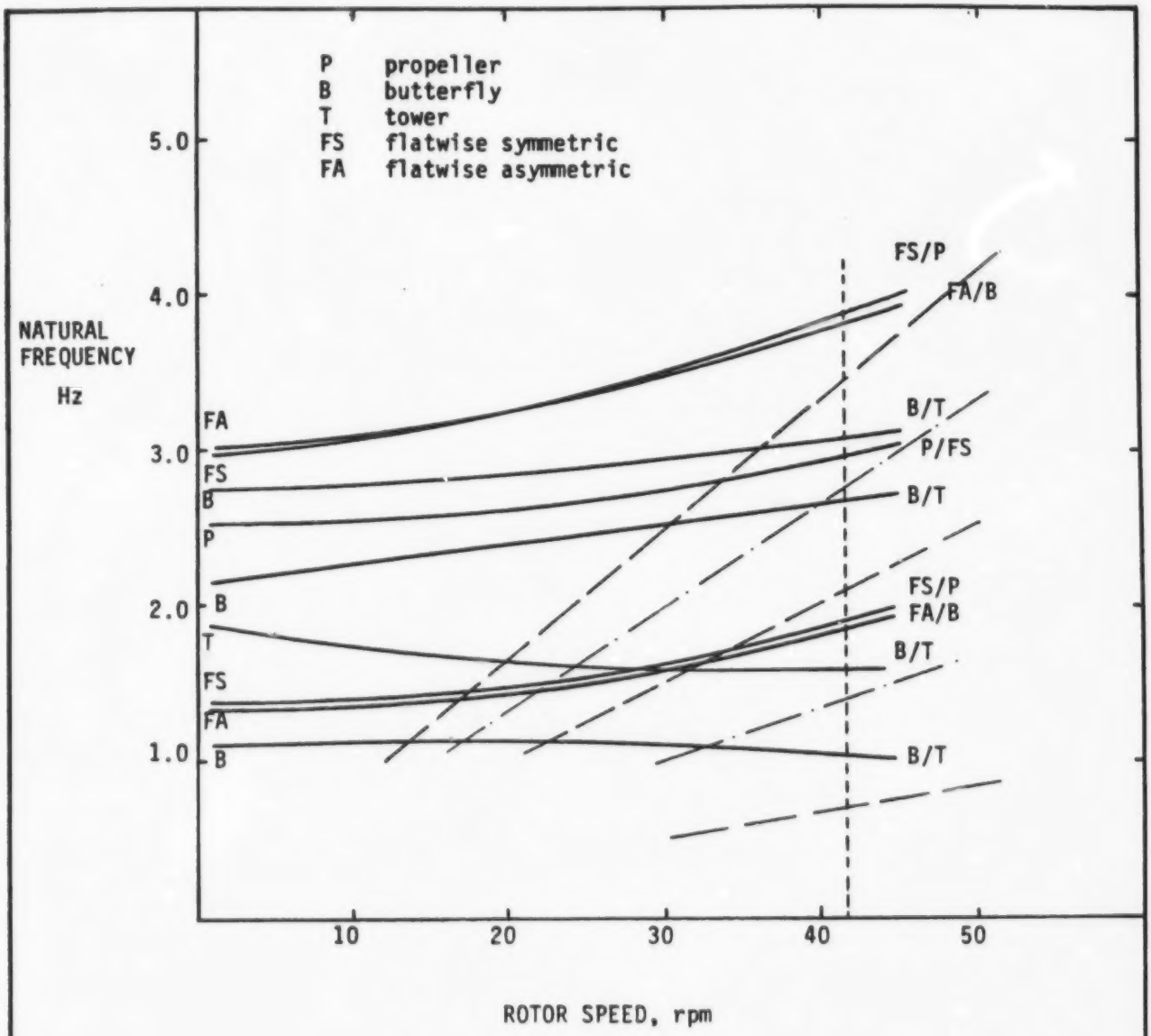


Figure 2.4. Natural Frequencies vs. Rotor Speed
Rotor #1 (Constant Chord)

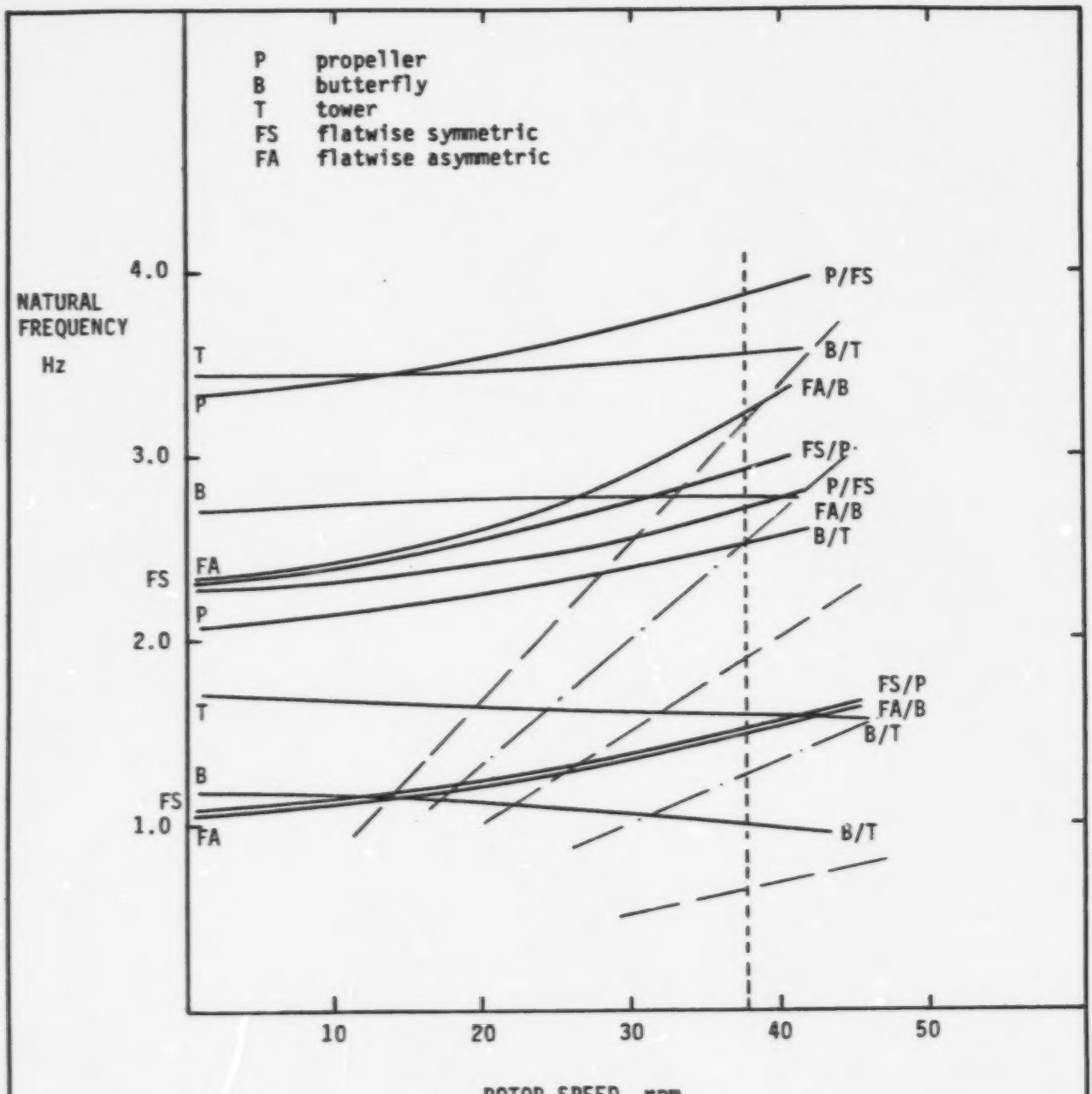


Figure 2.5. Natural Frequencies vs. Rotor Speed
Rotor #2 (Tapered Chord)

TABLE 2.2. SUMMARY OF STEADY STATE RESPONSE AT 45 MPH.
CONSTANT CHORD ROTOR

Item	Frequency 0P	1P	2P	3P	4P	5P	RMS of Cyclic Stresses
blade near lower root trailing edge stress	18.12 (2,630)	12.33 (1,790)	1.17 (170)	11.64 (1,690)	1 (150)	2.2 (320)	12.12 (1,760)
inner face stress	.21 (31)	.62 (90)	1.48 (215)	1.08 (157)	.77 (112)	1 (145)	1.63 (238)
blade near lower strut trailing edge stress	11.91 (1,730)	9.16 (1,330)	2.55 (370)	7.85 (1,140)	2.27 (330)	1.24 (180)	8.89 (1,290)
inner face stress	0.36 (53)	3.74 (543)	5.11 (742)	3.62 (525)	1.25 (182)	2.05 (297)	5.43 (788)
blade near upper strut trailing edge stress	9.78 (1,420)	9.03 (1,310)	10.88 (1,580)	6.13 (890)	1.59 (230)	.7 (100)	7.85 (1,140)
inner face stress	0.45 (65)	3.34 (185)	7.3 (1,060)	5.73 (833)	.44 (64)	1.33 (193)	7.05 (1,023)
mid-rotor column in-plane stress	0 (0)	15.6 (2,269)	.12 (17)	6.56 (953)	0.14 (2)	.79 (114)	12 (1,742)
out-of-plane stress	0 (0)	8.96 (1,300)	0.1 (15)	3.44 (500)	.02 (3)	.76 (110)	6.89 (1,000)

Units: MPa (psi)
Cyclic stresses are the ± amplitude

TABLE 2.3. SUMMARY OF STEADY STATE RESPONSE AT 45 MPH.
TAPERED CHORD ROTOR

Item	Frequency 0P	1P	2P	3P	4P	5P	RMS of Cyclic Stresses
blade near lower root trailing edge stress	24.4 (3,550)	9.29 (1,347)	2.73 (396)	14.00 (2,031)	0.74 (107)	1.76 (255)	12.0 (1,750)
inner face stress	10.3 (1,500)	0.18 (26)	0.82 (119)	0.34 (49)	0.28 (40)	0.39 (57)	0.72 (105)
blade near lower strut trailing edge stress	20.0 (2,900)	7.80 (1,131)	2.34 (339)	12.2 (1,776)	0.15 (22)	1.26 (183)	10.5 (1,513)
inner face stress	31.1 (4,513)	2.54 (369)	6.81 (988)	1.25 (181)	2.52 (366)	3.58 (520)	6.07 (880)
blade near upper strut trailing edge stress		8.96 (1,300)	2.18 (316)	8.85 (1,284)	0.92 (134)	2.53 (367)	9.23 (1,339)
inner face stress		1.34 (194)	12.24 (1,776)	3.68 (534)	1.06 (154)	2.56 (371)	9.29 (1,348)
mid-rotor column in-plane stress	18.2 (-2,645)	13.5 (1,961)	0.22 (32)	11.16 (1,615)	0.03 (5)	0.42 (61)	12.4 (1,796)
out-of-plane stress	18.2 (-2,645)	8.58 (1,245)	0.21 (31)	3.46 (502)	0.02 (13)	1.83 (266)	6.67 (967)

Units: MPa (psi)
Cyclic stresses are the ± amplitude

TABLE 2.4. SUMMARY OF RESPONSE TO SURVIVAL WIND.
CONSTANT CHORD ROTOR

	bending mt N.m (in.lb.)	axial force kN (lb)	bending stress ±MPa (±psi)
blade at lower root	1,084 (9,600)	54.7 (-12,300)	3.12 (453)
blade at lower strut	-5,874 (-52,000)	56.5 (-12,700)	16.8 (2,437)
blade at mid-rotor	8,586 (76,000)	52.0 (-11,700)	24.5 (3,566)
blade at upper strut	18,731 (165,800)	45.8 (-10,300)	53.6 (7,773)
upper bearing reaction		153.0 (34,400)	
mid-column bending	789,161 (6,985,000)		57.6 (8,360)

TABLE 2.5. SUMMARY OF RESPONSE TO SURVIVAL WIND.
TAPERED CHORD ROTOR

Location	bending mt N.m (in.lb.)	axial force kN (lb)	bending stress ±MPa (±psi)
blade at lower root	9,853 (-87,200)	79.6 (-17,900)	11.7 (1,693)
blade at lower strut	34,093 (-301,700)	64.5 (-14,500)	40.4 (5,861)
blade at mid-rotor	5,220 (46,200)	57.4 (-12,900)	15.2 (2,205)
blade at upper strut	48,478 (429,000)	49.4 (-4,100)	57.5 (8,343)
upper bearing reaction		166 (37,400)	
mid-column bending	833,300 (7,374,000)		51.7 (7,500)

strut-column connection was altered and for rotor #2 the strut-blade connection was made rigid.

For the length of blade closest to the roots of rotor #2 a steel core with sheet steel fairings was chosen. This design allows high strength friction bolted connections to be used at the roots and at the struts and makes use of the relative straightness of the blade in the vicinity of the roots.

2.2.3 Results

The principal result of these two tasks was a set of arrangement drawings which are appended to the report prepared on Tasks #3 and 4. A limited number of these drawings are included in the present report as Appendix A.

3.0 ENERGY PRODUCTION

In Task #1 (Rotor Configuration) calculations were made for the total energy production of the various rotors in certain wind regimes. None of those wind regimes corresponded exactly to the regimes to be found at the two selected locations (North Cape, Prince Edward Island, and the site of the 250 kW VAWT, Magdalen Islands). The energy output calculations were, therefore, repeated.

In practice, the wake from an upwind turbine will cause the energy output from a downwind turbine to be slightly decreased. This effect is sensitive to the spacing and orientation of the array of wind turbines and has been neglected in these calculations.

3.1 Prince Edward Island

The following information was received from the Atlantic Wind Test Site (AWTS) for the Indal 6400 machine.

mean annual windspeed (mid-rotor) = 7.40 m/s
(16.55 mph)
wind shear exponent = 0.16
Weibull distribution shape factor = 1.68

It is assumed that any windfarm will be located in the same region and, in the absence of other data, it is assumed that the wind regime will be the same as at AWTS. The results are summarized in Table 3.1.

TABLE 3.1 Energy Production at Selected Sites

	Indal 6400	Rotor #1 Constant Chord	Rotor #2 Tapered Chord
rotor height, m	36.6	38.6	41.4
rotor diameter, m	25.1	30.8	31.8
H/D ratio	1.46	1.25	1.29
swept area, m^2	605	786	891
rotor speed, rpm	45.0	41.0	38.0
max. elect. output, kW	520	520	520
PEI, V=7.40 m/s (mid-rotor), K=1.68			
annual energy, MWh	731	858	1005
% increase	0%	17.4%	37.5%
annual energy, MWh/m^2	1.20	1.09	1.13
Magdalen Islands, Case A			
V=8.60 m/s (mid-rotor), K=2			
annual energy, MWh	980	1152	1329
% increase	0%	17.6%	35.6%
annual energy, MWh/m^2	1.62	1.46	1.49
Magdalen Islands, Case C			
V=11.1 m/s (mid-rotor), K=2			
annual energy, MWh	1521	1724	1919
% increase	0%	13.3%	26.2%
annual energy, MWh/m^2	2.51	2.17	2.15

cut-off mid-rotor windspeed = 22.3 m/s (50 mph)

It should be noted that the windspeeds used in this section and in Table 3.1 refer to the mid-rotor height whereas those used in Table 1 of Tasks #1 and 2 refer to a 10m height with a wind shear exponent of 0.16.

3.2 Magdalen Islands

The following information was extracted from a request for proposals issued by Hydro Quebec for wind turbines to be located near the site of the DAF Indal 250 kW VAWT.

Case A (base of rotor at sea level)

mean annual windspeed (mid-rotor) = 8.6 m/s (19.2 mph)
wind shear exponent = 0.10
Weibull distribution shape factor = 2.0

Case C (base of rotor at 70m above sea level and a 15% speed-up assumed at equator height)

mean annual windspeed (mid-rotor) = 11.1 m/s (24.8 mph)
Weibull distribution shape factor = 2.0
wind shear exponent = 0.10

The results of these calculations are summarized in Table 3.1.

4.0 COST ESTIMATE

4.1 Costing Basis

The following assumptions were made when estimating costs.

- a total of twenty machines (of either rotor #1 or of rotor #2) will be built and installed (in one location);
- costs are in current 1987 Canadian dollars;
- all relevant customs, federal and provincial taxes are included;
- all overheads are included. Indal Technologies rates are those agreed upon with Supply & Services Canada for 1987;
- no fee for Indal Technologies has been included.

Many of the costs were obtained by comparison with known costs for the Indal 6400 (with adjustments for inflation). In some cases, such as the drive train, certain changes will be required but the costs of production will be similar.

Costs have been divided into recurring and non-recurring classes. The latter include initial or once-only costs such as engineering design and jig and tool manufacture. Transportation, installation, electrical connection, site preparation and operating costs have

also been included with the non-recurring costs. The recurring costs associated with each machine are summarized in Table 4.1 and the non-recurring costs are summarized in Table 4.2.

4.2 Rotor #1 (Constant Chord Blade)

This machine is the one that is most similar to the Indal 6400. The blades are made up of single extrusions although the section profiles differ and two new extrusion dies would be required.

The only item that shows an appreciable cost increase is the blades and connections. This is due to the greater length and weight of the blades. The struts incorporate the same hinge pin arrangement and the same precision machining is therefore necessary. The non-recurring costs in Table 4.2 show that while little additional engineering is required for the Indal 6400, a considerable design effort is involved in any new rotor. This amount is reflected in the proposal for Phase 2 of the current project.

Some of the arrangement drawings for this rotor are included as Appendix A.

The costs of transportation, installation and connection (see Table 4.2) differ very little with the wind turbine selected. Only if a larger crane were required for erection or if more than one railcar were required for transportation would these costs increase.

TABLE 4.1 Summary of Recurring Costs of Fabrication
(Includes all overheads and G & A, but no ITI fee)

Item	Indal 6400	Rotor #1 Constant Chord	Rotor #2 Tapered Chord
guy cables	$ 19,757	$ 20,122	$ 20,486
central column, upper bearing	88,743	98,763	111,584
lower coupling	8,823	8,823	8,823
blades & connections	66,117	88,288	94,911
struts & connections	35,175	38,693	20,057
gearbox	60,750	60,750	60,750
power module frame	77,967	77,909	77,969
motors	64,697	64,697	64,697
switchgear	19,139	19,139	19,139
control system	8,712	8,712	8,712
hydraulic system	17,861	17,861	17,861
testing, painting, packaging	8,700	8,700	8,700
production & manufacturing support	6,244	6,244	6,244
Total	$482,685	$515,241	$519,933
Cost Increase	0%	6.7%	7.7%

TABLE 4.2 Summary of Non-Recurring and Other Costs

Item	Indal 6400	Rotor #1 Constant Chord	Rotor #2 Tapered Chord
aluminum extrusion dies	56,700	113,400	131,000
aluminum extrusion: development costs	41,500	83,125	83,125
drill jigs & other dies - blades	69,255	69,255	76,071
drill jigs & templates - module	36,720	36,720	36,720
manufacturing & production engineering + PDM + QA	49,012	49,012	50,365
	$253,187	$351,512	$377,281
transportation to site	384,000	384,000	384,000
foundations	700,000	700,000	700,000
assembly & installation	720,000	720,000	800,000
electrical interconnection	400,000	400,000	400,000
high voltage system	1,200,000	1,200,000	1,200,000
roads, fences	500,000	550,000	600,000
central control system	80,000	80,000	80,000
control/maintenance building	300,000	300,000	300,000
Total	$4,537,187	$4,685,512	$4,841,281

4.3 Rotor #2 (Tapered Chord Blade)

Table 4.1 shows that the recurring costs for rotor #2 are only slightly greater than for rotor #1. This is due to design modifications involving the steel core blade adjacent to the roots and the simpler strut-blade connection. These two cost reductions tend to offset the cost increases associated with a larger column and longer blades.

The non-recurring costs of tooling are somewhat greater than for rotor #1 due to the addition of one extrusion die and the complexity of some blade splices. Adjustment has also been made for the greater on-site assembly time required.

5.0 CONCLUSIONS

5.1 Summary of Results

The annual energy produced by the three machines at the sites selected was presented in Section 3 (Table 3.1); the total recurring and non-recurring costs were presented in Tables 4.1 and 4.2. The overall cost effectiveness will depend on the manner in which the project is financed and the payment received from energy sales. However, the relative merits of the three rotors may be judged by dividing the total costs per machine by the annual energy produced by that machine.

This has been done for all machines and locations in Table 5.1. This table shows that the cost of energy will be reduced by 22% if the Indal 6400 at PEI is replaced by rotor #2. The reduction is more modest in the very high wind site (Magdalen Island, Case C, 15%) and ranges from only 6.7% to 10% for rotor #1.

These results confirm trends that have already been noted. The greater cost effectiveness of the tailored airfoil rotors is most apparent in the lower wind regimes and those with Weibull distribution shape factors greater than 2.0 (such as trade wind sites). It is anticipated that in a typical trade wind site the cost of energy could fall by as much as 30%. The cost decrease at the PEI site would have been greater if the Weibull shape factor had been greater than the 1.68 value reported.

TABLE 5.1 Cost of Energy Summary

Item	Indal 6400	Rotor #1 Constant Chord Blade	Rotor #2 Tapered Chord Blade
recurring costs per machine	$482,685	$515,241	$519,933
non-recurring costs per machine	12,659	17,576	18,864
transportation, installation, site, inter-connection, per machine	214,200	216,700	223,200
Total Costs per Machine	$709,544	$749,517	$761,997
Cost Increase	0%	5.6%	7.4%
PEI Site			
annual energy, MWh	731	858	1,005
total costs/annual energy, $/MWh	971	874	758
Cost Decrease	0%	10%	22%
Magdalen Islands, Case A			
annual energy, MWh	980	1,152	1,329
total costs/annual energy, $/MWH	724	651	573
Cost Decrease	0%	10%	21%
Magdalen Islands, Case C			
annual energy, MWh	1,521	1,724	1,919
total costs/annual energy, $/MWh	466	435	397
Cost Decrease	0%	6.7%	15%

NOTE: Engineering design costs have not been included for any of the three machines. This allows a true comparison

The marked superiority of rotor #2 over rotor #1 is due to two factors: one is the considerably greater energy production, and the other is the relatively small increase in production costs. The latter may be traced to the savings at the strut-blade connection and to the steel-core blade used near the roots.

It can be seen from Table 5.1 that approximately one-third of the total windfarm cost is associated with site activities. Of these, the installation of the high voltage transformer and connections is the greatest item.

The relative costs involved in a one- or two-machine prototype installation will not necessarily be in the same proportion as those presented here. There are more non-recurring costs associated with rotor #2 than with #1 due to the additional extrusion dies and tool fixtures required. By the same argument, production of more than 20 machines would make rotor #2 look even more attractive.

5.2 Recommendations

Based on the calculations presented in this and previous reports, the following recommendations are made.

(1) It is necessary to use the larger swept area and superior power coefficients of the tapered chord blade to obtain appreciable reductions in the cost of energy. Any further design work should therefore concentrate on rotor #2.

(2) Detailed design work should pay special attention to the design of the steel-cored blade and to the reliability of all blade connections.

(3) No consideration has been given in this preliminary study to aerodynamic losses at the blade splices or strut connections. Final design should give attention to these concerns.

6.0 REFERENCES

1. Darrieus, G.J.M., "Turbine Having Its Rotating Shaft Transverse to the Flow of the Current", US Patent No. 1-835-018, December 1931.

2. Malcolm, D.J., "Validation of the Forced Response of Darrieus Rotor Vertical Axis Wind Turbines", Sixth Biennial Wind Energy Conference and Workshop, American Solar Energy Society, Minneapolis, June, 1983.

3. "Technology Development Study of Vertical Axis Aerogenerator Systems Yielding the Lowest Cost of Energy", DSS Canada contract 25SR-31155-0-4605 by DAF Indal Ltd., May 1984.

4. G.M. Gregorek, P.C. Klimas, "Tailored Airfoils for Wind Turbine Applications", 4th ASME Wind Energy Symposium, Dallas, Feb. 1985.

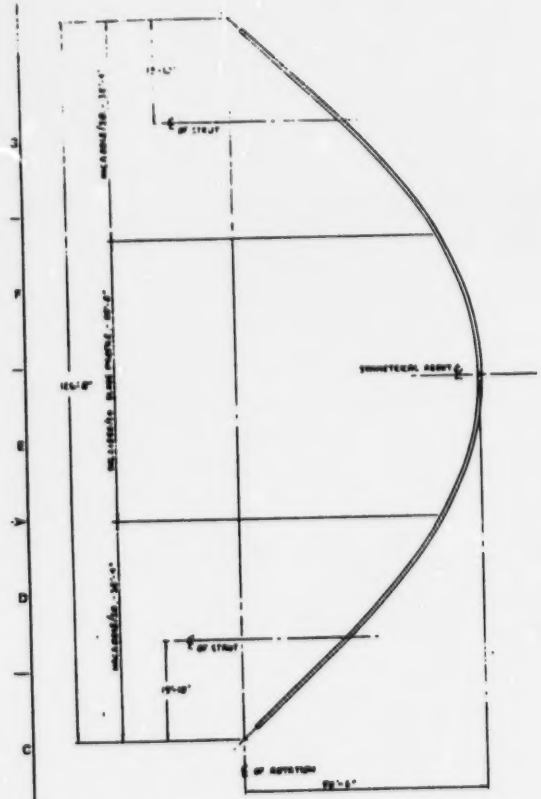
5. G.M. Gregorek, "Airfoil Design for Wind Turbines", Wind Turbine Aerodynamics Seminar, Sandia National Laboratories, Albuquerque, 26 March 1985.

6. D.E. Berg, "Structural Design of the Sandia 34-m Vertical Axis Wind Turbine", 4th ASME Wind Energy Symposium, Dallas, Feb. 1985.

7. P. Klimas and M. Worstell, "Testing of the SNL 17-m Research Turbine with Natural Laminar Flow Blade Elements", Wind Turbine Aerodynamics Seminar, Sandia National Laboratories, Albuquerque, March 1986.

APPENDIX

Selected Arrangement Drawings

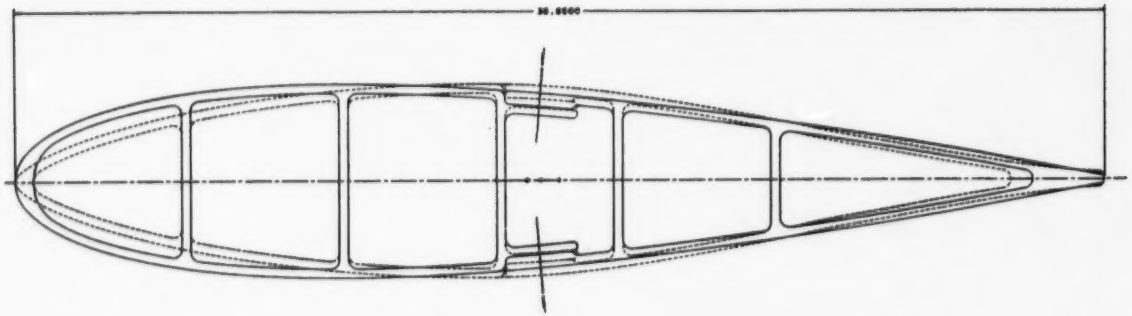


BLADE ASSEMBLY
LOCATION OF LEADING EDGE
NOT TO SCALE

NOTES:
1. DIMENSION REQUIRED AS LISTED AND
DIMENSION REQUIRED WITH EXTENSIONS FROM 383
COMBINED, FROM 4.87 CONSIDERED AND ELIMINATING ITEM 4.87

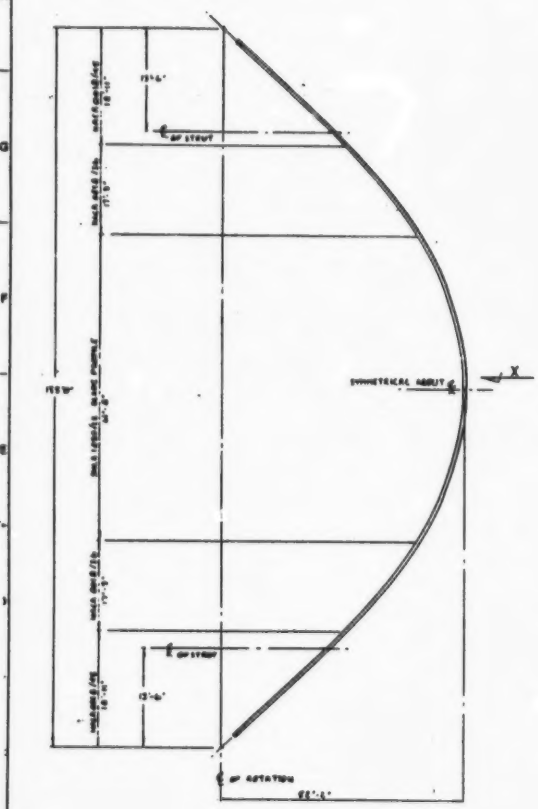
2. THIS BLADE ASSEMBLY WITH 50" CORD WILL BE VERY SIMILAR
TO THE 60" CORD BLADE RECENTLY PRODUCED FOR THE "LEGEND"
FOR THIS ESTIMATE USE ACTUALS FOR THE "LEGEND" WITH CHANGES:
a/ SUBSTITUTE BLADE EXTENSIONS FROM NO. 2 WEB FOR EX 139
b/ ADD ONLY PIN HOUSING 1 DIFFERENT SIZE OF EXTENSIONS
SIMILAR TO EX 139-1 AND -2
c/ ADD ONLY FOR A SPLICE PLATE SIMILAR TO 2579-040-3 BUT WITH
A PROFILE 0.090" FORGED. ALLOW ITS HANDLE TO MATCH THE
E BLADE PROFILES MACHINED/SP AND SHAVED/SP

SEE NOTE 2	1	2579-49	BOLT TO BLADE ASSEMBLY	11
	1	2579-040	BLADE ASSEMBLY	10
				9
				8
				7
				6
				5
SEE NOTE 1	2		BLADE EXTENSION MACH 0.018"/30" R + 30 FT.	4
	2		BLADE EXTENSION MACH 0.018"/30" R + 84 FT.	3
	1		BLADE EXTENSION SHEET 0.063"/30" R + 84 FT.	2
	1		BLADE EXTENSION SHEET 0.063"/30" R + 84 FT.	1
			BLADE ASSEMBLY	
	QTY	MATERIAL	DESCRIPTION	



VARY BLADE ASSEMBLY
HIGH ENERGY ROTOR
CONSTANT BLADE CORD

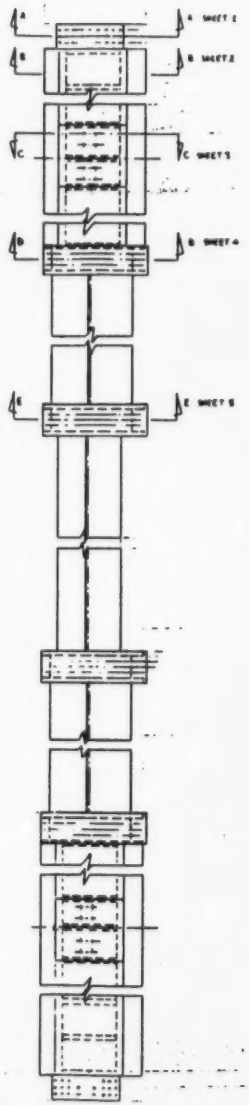
E 36334 SK-2357



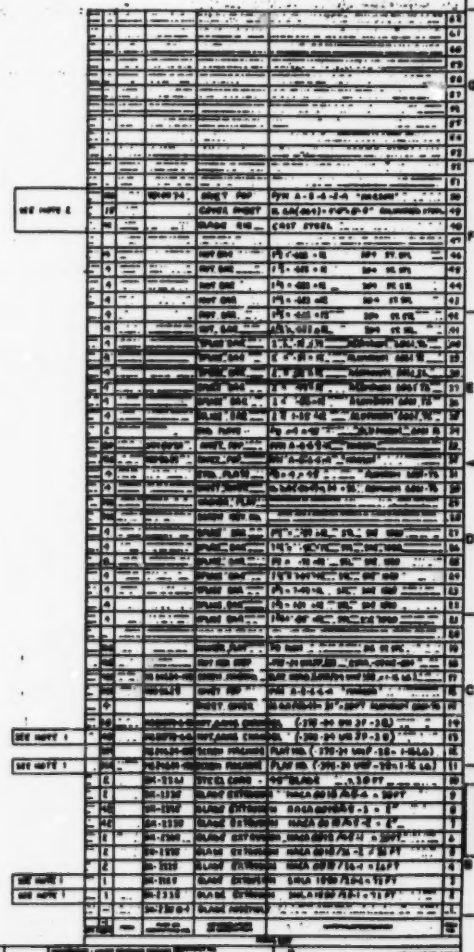
BLADE ASSEMBLY
LOOKING AT LEADING EDGE
NOT TO SCALE

NOTES:

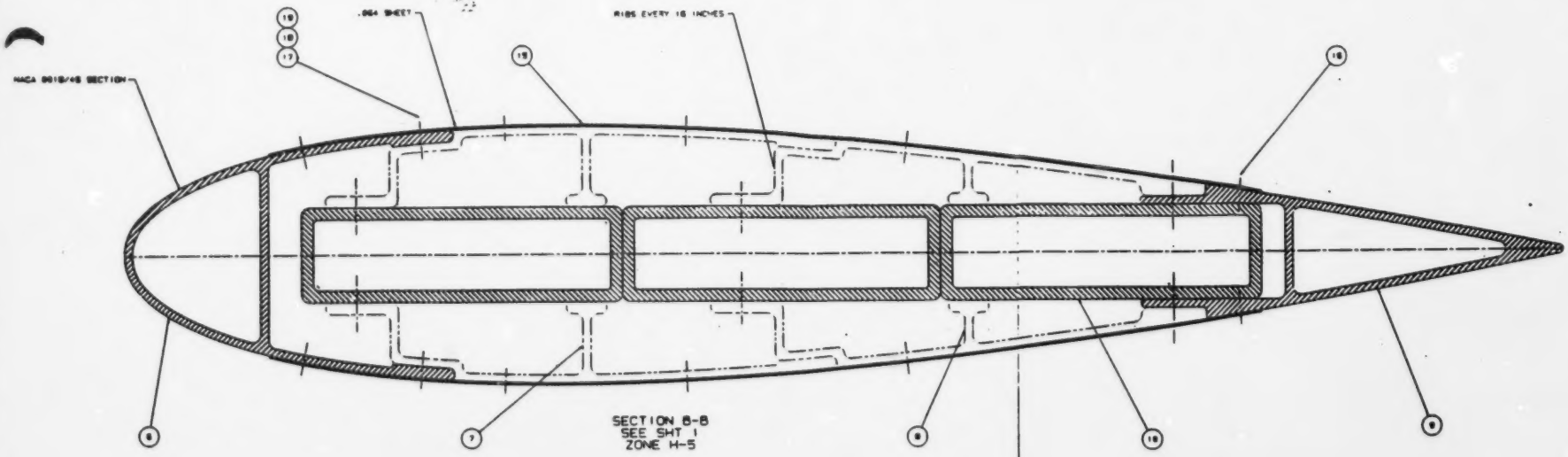
1. ROTATION REQUIRED AS LISTED AND ROTATION REQUIRED WITH ITEM E AND D COMBINED AS ONE EXTRUSION AND ELIMINATING ITEM 11 AND 12
2. ROTATION REQUIRED WITH 90° CURVED BLADE CONSTRUCTED AS SHOWN ON SHEET 2 AFD.
   ROTATION REQUIRED WITH 90° CURVED BLADE CONSTRUCTED AS SHOWN ON SHEET 6 AFD SUBSTITUTING ITEMS 10 AND 11 AND ITEMS 4,7,8,9 & 12



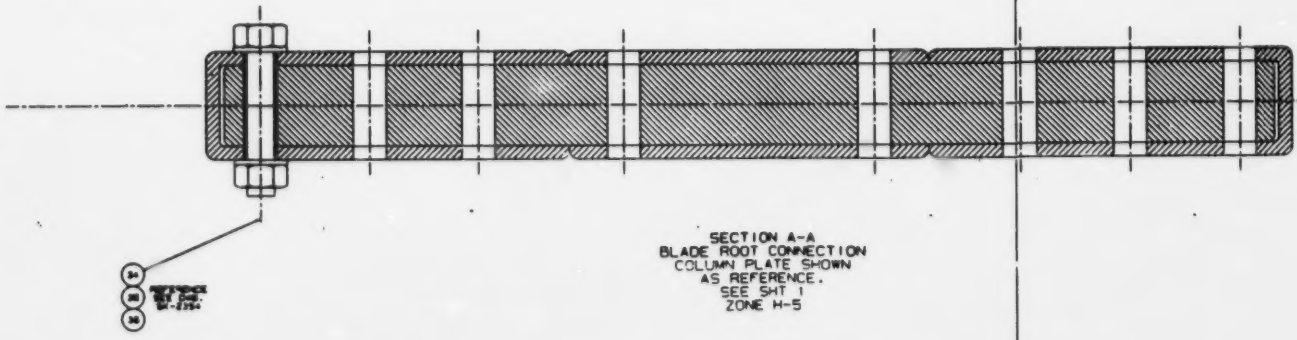
DEVELOPED ELEVATION ON 'X'
SCALE 1/4



		WHIT BLADE ASSEMBLY HIGH ENERGY ROTOR TAPERED BLADE CARD
	E 36334	SK-2358



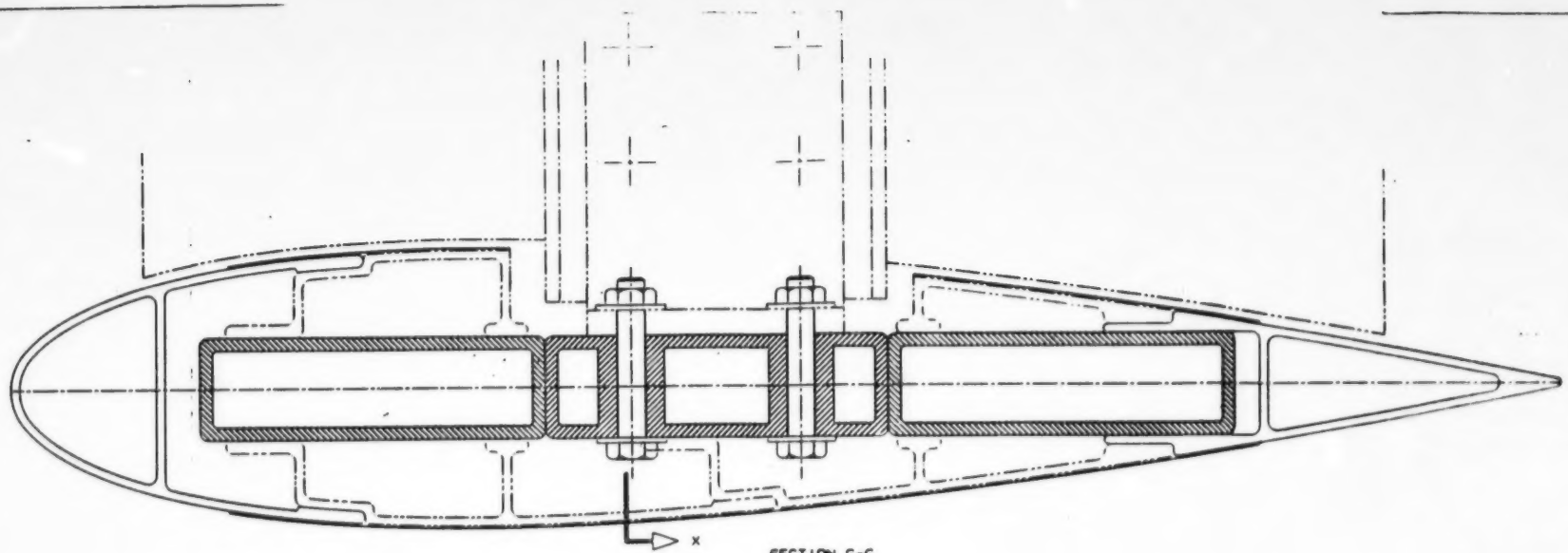
SECTION B-B
SEE SHT 1
ZONE H-5



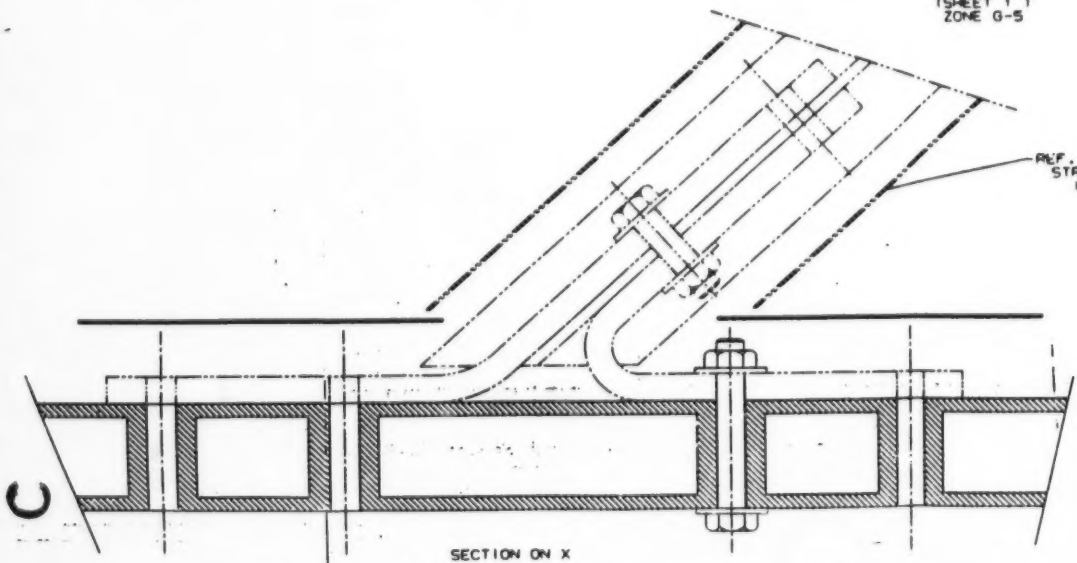
SECTION A-A
BLADE ROOT CONNECTION
COLUMN PLATE SHOWN
AS REFERENCE.
SEE SHT 1
ZONE H-5

VANE BLADE ASSY-
HIGH ENERGY ROTOR
TAPERED BLADE CONF

H 36334 SK-2358



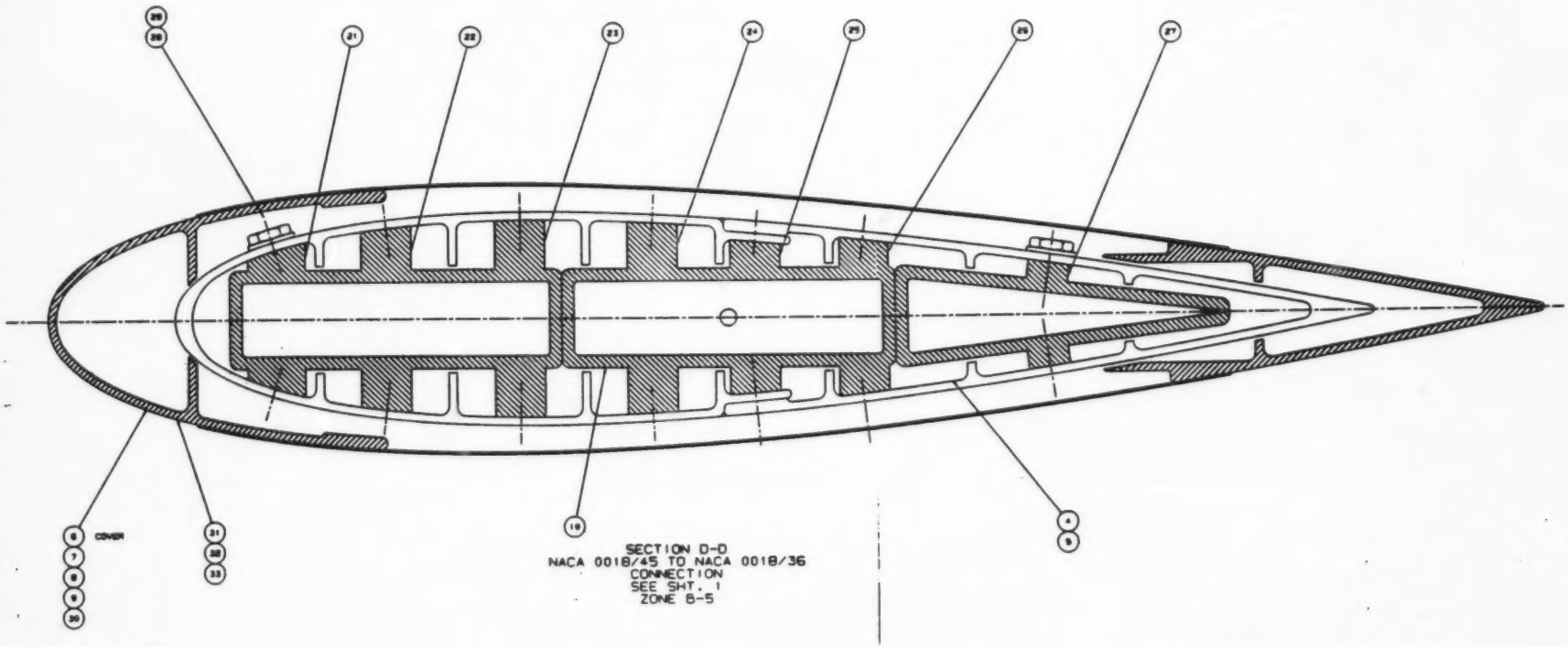
SECTION C-C
(SHEET 1)
ZONE G-5



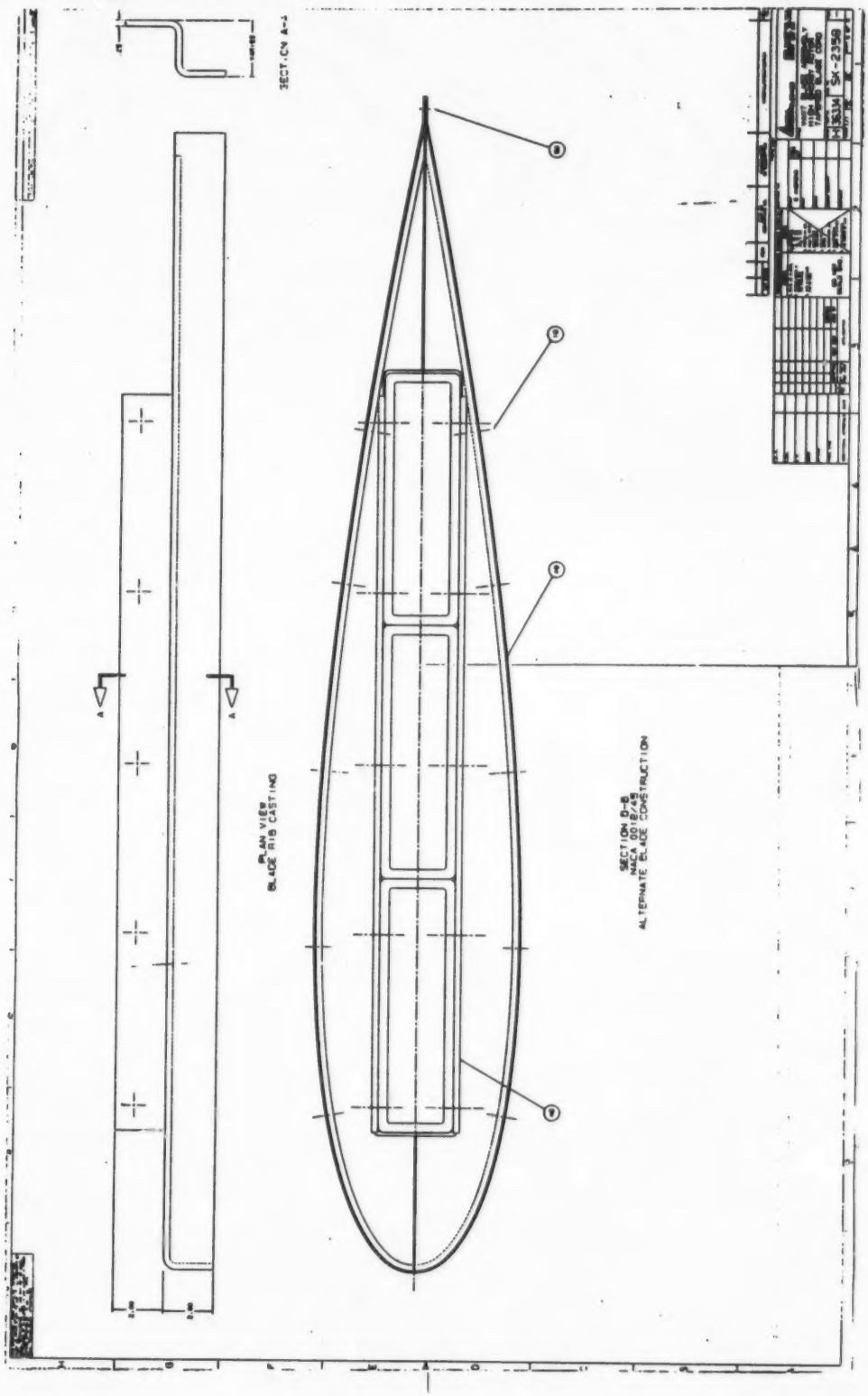
SECTION ON X

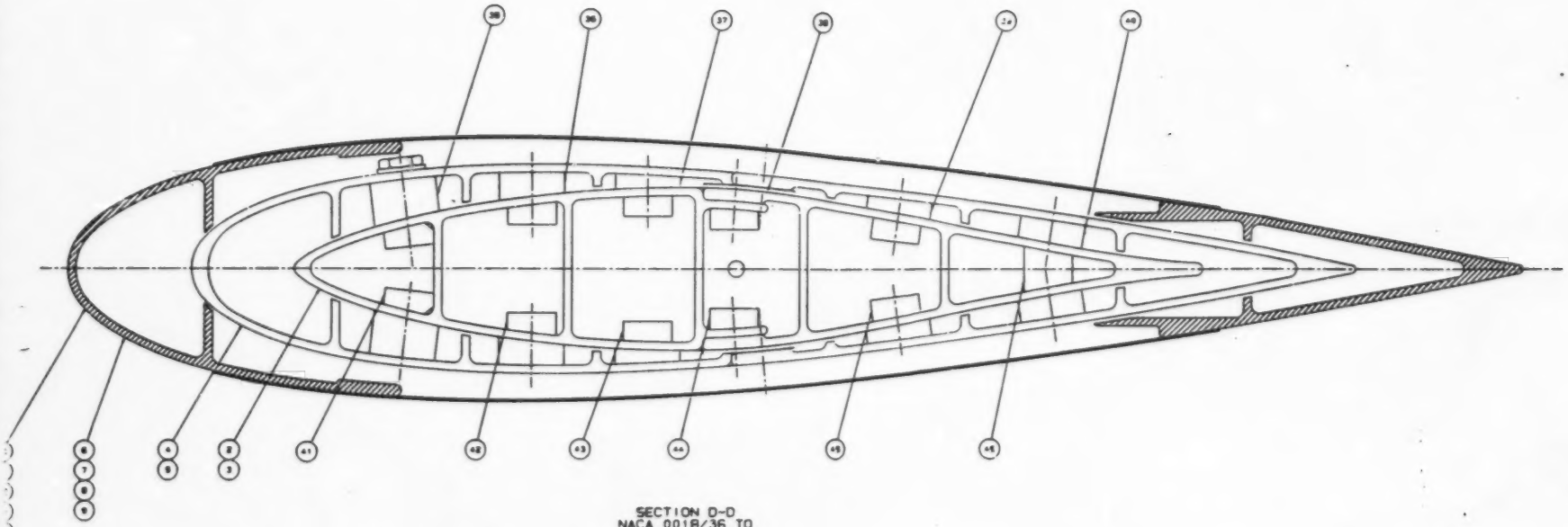
VARY BLADE ASSY.
HIGH ENERGY ROTOR
TAPERED BLADE

H 36334 SK-2358



SECTION D-D
NACA 0018/45 TO NACA 0018/36
CONNECTION
SEE SHT. 1
ZONE B-5


SECT. ON A-A
PLAN VIEW
BLADE RIB CASTING
SECTION B-B
NACA 0018/45
ALTERNATE BLADE CONSTRUCTION



SECTION D-D
NACA 0018/36 TO
SNLA 1650/28
CONNECTION
SEE SHT 1
ZONE D-5

VANT BLADE ASSY.
HIGH ENERGY ROTOR
TAPERED BLADE CO
H 36334 SK-2358